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Comparing one-way sideswipe crash treatments on curved multilane roads: Estimating accident modification factor for partial physical lane separation treatment

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Abstract

Road crashes are more prevalent on curved road sections compared to straight, multilane, one-directional sections. This study focuses on a driving behavior known as "curve-cutting," a major cause of sideswipe crashes. To address this issue, the study evaluates the perceived effectiveness of partial physical lane separation treatments (PPLSTs) within the road pavement layer in Lebanon. Three types of PPLSTs were introduced: raised pavement markers (RPM), transverse rumble strips (TRS), and scratched asphalt surfaces (SAS). A questionnaire survey assessed the perceived effectiveness of PPLSTs on driving behavior and identified the main causes of crashes on curved road sections. Results indicate that combined high-speed and reduced-attention driving, followed by high-speed driving alone, are the primary causes of crashes. Most respondents perceive TRS as the most effective solution, followed by SAS. These findings are used in a multicriteria decision analysis to preliminarily estimate the accident modification factors (AMF) for the PPLSTs. The preliminary estimated AMF values for TRS and SAS are less than 0.94 and 0.67, respectively. The results are crucial for developing targeted road safety measures and policies, providing insights for implementing artificial intelligence algorithms in autonomous vehicles.

Keywords: Curved road sections, driving behavior, partial physical lane separation treatments (PPLSTs), perceived effectiveness, road traffic crashes, safety measures.

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1. Introduction

Road traffic accidents remain a significant global concern, prompting extensive research and discussions on various contributing factors. While much attention has been given to aspects such as driver behavior and speed limits, the influence of road alignment characteristics, particularly in curved sections, has been somewhat overlooked. This study aims to explore the background of road traffic accidents and emphasize the role of curved roads and their indirect impact on safety, to investigate, preliminarily, the effectiveness of some physical solutions. The subsequent detailed information explores the nuanced relationship between road curvature, driver behavior, and accident occurrence, providing insights into specific accident types and proposing a novel road safety measure.

1.1. Review of Existing Research on Traffic Crashes in Curved Road Sections

Within the context of road traffic crashes, a number of literature documents have discussed this issue. Road alignment characteristics, including slope direction, elevation difference value, curve radius, and transition curve ratio, are often overlooked in discussions about road traffic safety.

However, these alignment factors play a crucial role in causing traffic accidents indirectly. Their impact is particularly notable in the frequent occurrence of three specific accident types: rear-end collisions, collisions with fixtures, and rollovers [1, 2]. More particularly, poor driving interaction and behavior at curved road sections are known to cause traffic crashes [1, 3-7]. In more detail, road curves have higher crash rates than straight sections of similar length and traffic composition [6]. The author stated also that the difference comes to be noticeable at radii less than 1000 meters and that the increase in crash rates becomes major, specifically at radii below 200 meters. Alike, Khuzan and Al-Jumaili [8] indicated in their study that curves, whether single or multiple, posed the greatest risk when their radius was less than 200 meters. Similarly, Calvi [5] indicated that road crashes are more likely to occur on curves than on straight roadway segments. The author stated that the driver's behavior along the curved road sections, associated with his/her perception of the road geometry aspects such as the radius, transition curve and visibility, is the main factor responsible for road crashes in curved sections. The author indicated also that the evaluation of the effects of curve features and speed limits on driving behavior is still representing a critical issue for road design and traffic safety. Moreover, the excessive running speed of vehicles is defined as one of several risk factors that affect the occurrence of a road crash and its severity, especially on highway curves [4]. The authors found that the speed reduction induced by the perceptual treatment measures could reduce the number and rates of traffic crashes on curved road sections. Similarly, Cheng et al. [9] identified the risk factors responsible for traffic accidents in curved road sections in decreasing order of importance as follows: vehicle speed, curve radius, vehicle type, adhesion coefficient, hard shoulder width, and longitudinal slope. The literature within its few articles on this topic has investigated the driving behaviors on curves. The main outcomes indicated a general behavior not aligned with the geometric aspects of these curves. This behavior is depicted as cutting curves and changing lanes, leading to an elevated crash rate in comparison to straight road sections. These studies have preliminarily linked this behavior to the cause represented by the operating speed of vehicles. However, the root causes behind this behavior on curved sections have not yet been investigated. These causes could comprise: (i) the visual perception of drivers, (ii) their physical movement (ruled mainly by centrifugal forces) during the maneuvers, and (iii) their previous knowledge of the elevated crash rates, particularly on such road sections (due to slippage mainly).

1.2. Conceptual Context of the Study

This study inspects, through a questionnaire survey, whether the implementation of a new road safety measure could prevent drivers from changing lanes or doing cutting curves maneuvers, and thus reduce the number and rates of traffic crashes, in particular the sideswipe accidents. This new road safety measure is defined by the installation of Partial Physical Lane Separation Treatment (PPLST) within the road pavement against the sideswipe crash patterns (in curved road sections) illustrated in Figures 1a and 1b. Then the objectives of this study are explained as: (i) identifying, according to the scientific literature and mainly the documents of the American Association of State Highway and Transportation Officials [10] the most efficient PPLST types, (ii) investigating the perceptions of drivers regarding the causes of traffic crashes on curved road sections and the effectiveness of certain PPLST measures, (iii) comparing the perceived effectiveness in general and according to gender, age classes as well as the type and size of used vehicles, and (iv) estimating the possible Accident Modification Factors (AMFs) of certain PPLSTs. In that context, the Accident Modification Factor, used to estimate the effectiveness of different safety countermeasures, is depicted as a ratio that represents the expected change in the number of crashes that will occur after a safety countermeasure is implemented. The AMF is calculated as the ratio of the number of accidents after the implementation of a safety countermeasure to the one before the implementation of this particular countermeasure. The AMFs are typically derived from empirical studies or crash data analysis. Nevertheless, generally, in the absence of observed data, surrogate measures, as comparable locations and situations of accidents (traffic volume, speed, geometric design features…), as well as expert judgments, could be employed to make an approximate estimation of AMFs. In this study, the perception of users coupled with data provided by the literature review [10] is used to estimate the AMFs for the proposed accident countermeasures (PPLSTs). The contribution to the scientific literature of this research lies in its comprehensive investigation into the effectiveness of a novel road safety measure, the Partial Physical Lane Separation Treatment (PPLST), in preventing or reducing sideswipe accidents on curved road sections. The study is distinct in its focus on addressing a specific crash pattern and proposes the installation of PPLST within the road pavement as a countermeasure. The uniqueness of this research is further underscored by its multi-faceted objectives. Firstly, it aims to identify the most efficient types of PPLST based on a thorough review of scientific literature, particularly referencing documents from the American Association of State Highway and Transportation Officials. Secondly, it explores the perceptions of drivers regarding the causes of traffic crashes on curved road sections and assesses the effectiveness of specific PPLST measures. The study goes beyond a general evaluation and explores variations in perceived effectiveness concerning gender, age classes, and the type and size of vehicles used. Additionally, the current study endeavors to estimate Accident Modification Factors (AMFs) for certain PPLSTs, contributing to the understanding of the potential impact of these safety measures.

The study advances several hypotheses related to driving behavior on curved road sections and the potential impact of PPLSTs. It is hypothesized that PPLSTs could enhance driving behavior on curved road sections and reduce considerably crash and conflict rates and numbers. It is also hypothesized that the super-elevation and the radial shape of curves would normally push the vehicle to move out of its lane. A third hypothesis to be tested proposes that the limited visual capacity on curves leads drivers to change lanes alternatively in order to increase their visual scope.

Moreover, the previous drivers experience in crashes on curved road sections, as of slippage/losing control of vehicles, leads them to prevent driving in a sharp way (by pushing the steering wheel sharply to left/right). Preventing sharp driving behavior allows vehicles to be in conformity with the curve shape, by keeping them under less “stressed maneuvers” to minimize the effects of centrifugal forces in order to finally prevent slippage. It could be hypothesized also that the increased efforts of driving and the excessive psychological stress on curves would have also negative effects on driving behaviors.

It is noteworthy that this research investigates only the causes of traffic crashes and the efficacy of PPLSTs from the point of view of car drivers without taking into consideration different scenarios related to road attributes as: (a) radius of the curve, (b) the number of lanes, (c) speed limits, (d) curvature direction (to the left or to the right), (e) vertical direction of the curve (horizontal, downward, upward), and (f) the location of the vehicle on the inner or outer lane. The results of this research will show the effects of the proposed safety measures on driving behaviors and the rate of crashes. The study combines different scientific fields as the human sciences, pavement engineering technology, traffic safety, new legislation and policies. Moreover, this research could provide some useful insights for implementing the artificial algorithm of autonomous vehicles (AVs). This could be achieved through (a) creating dynamic algorithms for AVs that can adapt to varying road conditions and scenarios, (b) enhancing the decision-making processes of AVs, (c) improving the adaptability of algorithms to diverse user profiles, (d) developing comprehensive algorithms that consider not only technical aspects but also human and legal considerations, and (e) benefiting AVs in navigating complex factors influencing road safety. The research presented in this paper holds significant relevance for policymakers, transport operators, road and pavement engineers, and road users. The insights gained from this study have the potential to guide enacting new coherent transport policies and preparing road safety contingency plans. Moreover, they may provide a future outlook on new approaches for transport safety for operators and service providers. The paper is organized as follows: Section 2 presents the methodology and data collection techniques. Section 3 highlights the obtained results, which are discussed in more detail in Section 4. Section 5 summarizes the paper, emphasizing the originality of the methodology, and proposes future research subjects related to this research as potential extensions.

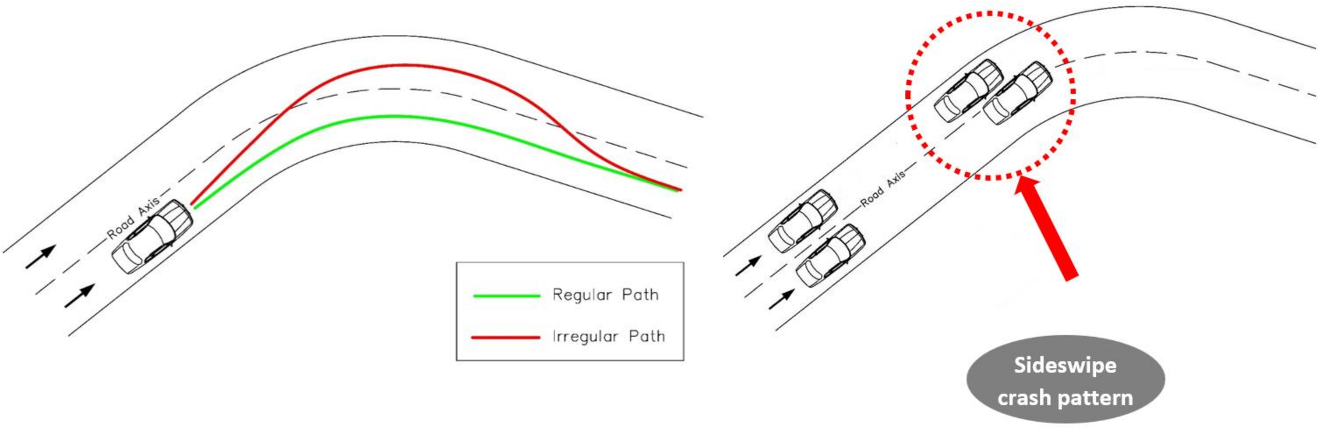

Figure 1a.
Cutting curve-Scenario 1: Inner to outer lane.

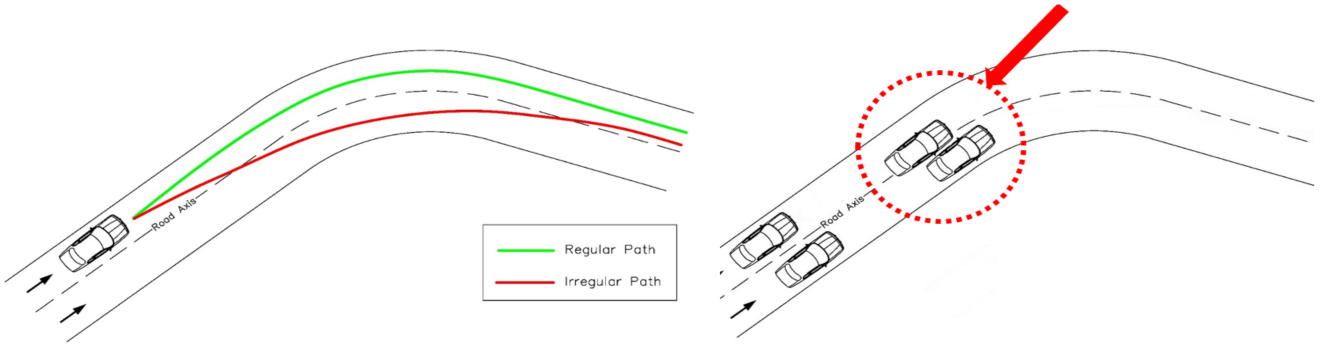

Figure 1b.
Cutting curve-Scenario 2: Outer to inner lane.

2. Methodology and Data Collection

The adopted methodology combines the fields of human sciences, pavement engineering and traffic safety science. This multidisciplinary approach will give an overview of the interrelated bidirectional impacts of these scientific fields. The first part of the methodology is the identification of the most efficient PPLST types, according to the literature review, for car traffic accidents, particularly in curved road sections. The second part of the methodology is explained by designing and conducting a questionnaire survey to determine the perceived main causes of road crashes on curved road sections as well as the expected impacts of different PPLSTs on driving behaviors against these causes. In other words, the study will check people's perceptions of the effectiveness of different PPLSTs, which will be stimulated/triggered by the dynamic road-vehicle vibrations in addition to the visual perception. The third part of the methodology is presented by the application of the Analytical Hierarchy Process (AHP) to compare via pairwise comparison matrices the effects of the different PPLSTs on the frequency of road crashes in curved road sections. This comparison will (a) indicate the type of PPLST having the most powerful capability to reduce the crash rates and (b) lead to a preliminary estimation of the AMFs for the most powerful PPLST.

2.1. Identification of the Most Relevant and Effective PPLST

According to the American Association of State Highway and Transportation Officials (AASHTO) [10], several types of lane separation treatments for both one-directional multilane and two-directional roads are identified and checked as indicated in Table 1. These treatments are divided into seven categories: (A) Median barriers, (B) post-mounted delineators, (C) raised median, (D) speed humps, (E) snowplowable permanent raised pavement markers (RPM), (F) Transverse rumble strips (TRS), and (G) scratched asphalt surface (SAS). The following subsections present in more detail. Table 1 presents the road safety effectiveness of these treatments as indicated in the Highway Safety Manual [10].

2.1.1. Median Barriers, Post-Mounted Delineators

Median barriers and post-mounted delineators are implemented to improve road safety by mitigating the risk of head-on collisions and facilitating driver navigation through curves and lane changes. For instance, the installation of median barriers on rural four-lane freeways has demonstrated notable reductions in cross-median crashes [11]. The use of median barriers and post-mounted delineators may, however, entail certain unfavorable consequences on traffic safety [12-14]. Notably, when a vehicle collides with a median barrier or post-mounted delineator, it can result in considerable damage to the vehicle. Furthermore, while median barriers prove effective in reducing head-on collisions, their effectiveness in preventing other crash types, such as side-swipe collisions or single-vehicle run-off-road crashes, may be limited. Additionally, there exists a potential for secondary collisions, as a vehicle that impacts a median barrier may be redirected back into traffic, thereby engendering additional collisions with other vehicles. Differently, and with respect to the operation speed of vehicles, median barriers could suddenly, at curves, oblige drivers to make a sharp reduction of speed which could disrupt the smooth flow of traffic and may cause accidents. With respect to these considerations of crash and damage risk of vehicles these types of treatments are not taken into consideration as a PPLST in this study.

2.1.2. Raised Median and Longitudinal Speed Humps

The implementation of small raised medians (for example 20 centimeters width) or longitudinal humps, to be placed (longitudinally) as/on centerline separating lanes of one-direction curved road section (concept developed from the curb-separation for cycling lanes as indicated in the Google maps photos from Paris: Figures 2a and 2b), were proposed by the author of this research as treatment. However, and with particular considerations of the destabilization of vehicles, when they pass over these treatments, due to changes in vertical levels at high speeds coupled with centrifugal forces of the curved road sections, this type of treatment is not taken into consideration in this study. This does not mean that additional studies about the geometric aspects of these treatments, especially in terms of height and width, should not be conducted.

Table 1.
Safety effectiveness of treatments according to the Highway Safety Manual [10].

Category	**Treatment**	**Setting (Road type)**	**Traffic Volume (AADT)**	**Accident type (Severity)**	**AMF**	**Std. Error**
A	1- Install any type of median barrier	*Unspecified (Multi-lane divided highways)*	AADT of 20,000 to 60,000	All types (Fatal)	0.57	0.1
				All types (Injury)	0.7	0.06
				All types (Severities)	1.24	0.03
	2- Install steel median barrier			All types (Injury)	0.65	0.08
	3- Install cable median barrier				0.71	0.1
B	4- Install post-mounted delineators	Rural (Two-lane undivided)	Unspecified	All types (Injury)	1.04	0.1
				All types (Non-Injury)	1.05	0.07
C	5- Provide a raised median	Urban (Two-lane)	Unspecified	All types (Injury)	0.61	0.1
		Urban (Arterial Multi-lane)	Unspecified	All types (Injury)	0.78	0.02
				All types (Non-Injury)	1.09	0.02
		Rural (Multi-lane)		All types (Injury)	0.88	0.03
				All types (Non-Injury)	0.82	0.03
D	6- Install speed humps	Urban/Suburban (Residential Two-lane)	Unspecified	All types (Injury)	0.6	0.2
E	7- Install snowplowable permanent raised pavement markers (RPMs)	*Rural (Two-lane with radius > 1640 ft)*	0 to 5,000	Nighttime All types (All severities)	1.16	0.03
			5,001 to 15,000		0.99	0.06
			15,001 to 20,000		0.76	0.08
		Rural (Two-lane with radius ≤ 1640 ft)	0 to 5,000		1.43	0.1
			5,001 to 15,000		1.26	0.1
			15,001 to 20,000		1.03	0.1
		Rural (Four-lane freeways)	≤ 20,000		1.13	0.2
			20,001 to 60,000		0.94	0.3
			> 60,000		0.67	0.3
F	8- Install centerline rumble strips	*Rural (Two-lane)*	5,000 to 22,000	All types (Severities)	0.86	0.05
				All types (Injury)	0.85	0.08
				Frontal and opposing-direction sideswipe (All severities)	0.79	0.1
				Frontal and opposing-direction sideswipe (Injury)	0.75	0.2
G	9- Transverse rumble humps	This treatment appears to reduce accidents of all severities on urban and suburban arterials; however, AMF is not available for this treatment.				

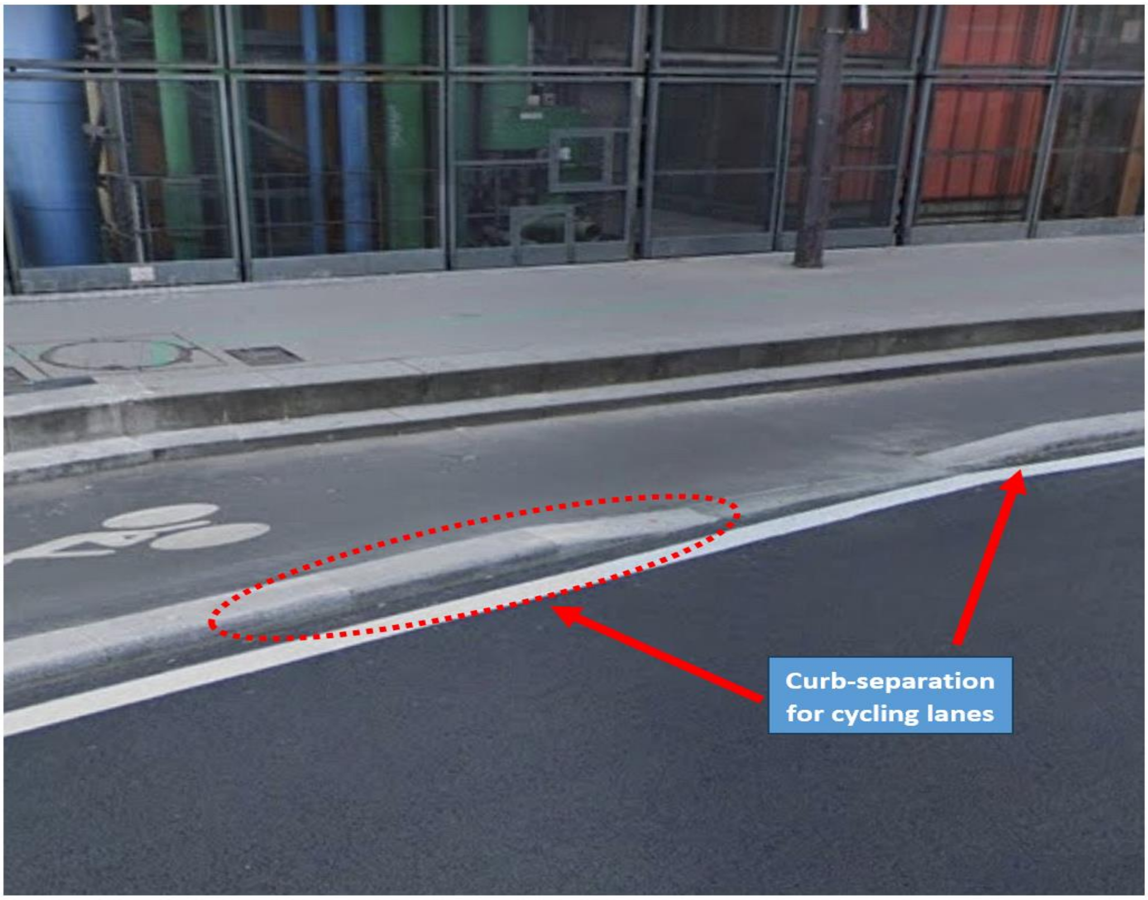

Figure 2.
Curb separation for cycling lanes.

2.1.3. Snowplowable Permanent Raised Pavement Markers

Several studies discussed the effects of raised pavement markers (RPMs) on roadway safety by enhancing visibility for drivers, providing visual guidance for navigation, especially in low-light conditions or during inclement weather, as well as in areas with poor signage. This helps drivers stay within their lanes and reduces the risk of lane drifting or crossing, alerting drivers to changes in the road, such as intersections, upcoming curves, and pedestrian crossings. Even so, the effects of RPMs may vary, and the outcomes can be either positive or negative depending on traffic conditions and roadway geometry. In more detail, the differing impacts on crash rates are based on traffic volume associated with lower design standards, such as narrower lanes and shoulders...

For instance, providing improved delineation such as RPMs, for low volume traffic (Average Annual Daily Traffic (AADT) less than 20,000), may cause drivers to increase their speeds and thus increase the crash rates [10, 15]. Nonetheless, for high traffic volume (AADT > 20,000), different studies were conducted to analyze the crash rates on roadways with RPMs (RPMs) and compare them to those on roadways without RPMs. The results showed that, on average, the presence of RPMs on roadways may contribute to a significant reduction in crash rates, suggesting their effectiveness in enhancing road safety [10, 16]. This is why implementing RPMs requires particular consideration, as it could represent an important treatment to reduce crash rates in road curvature. Figure 3 shows the setting-up of RPMs.

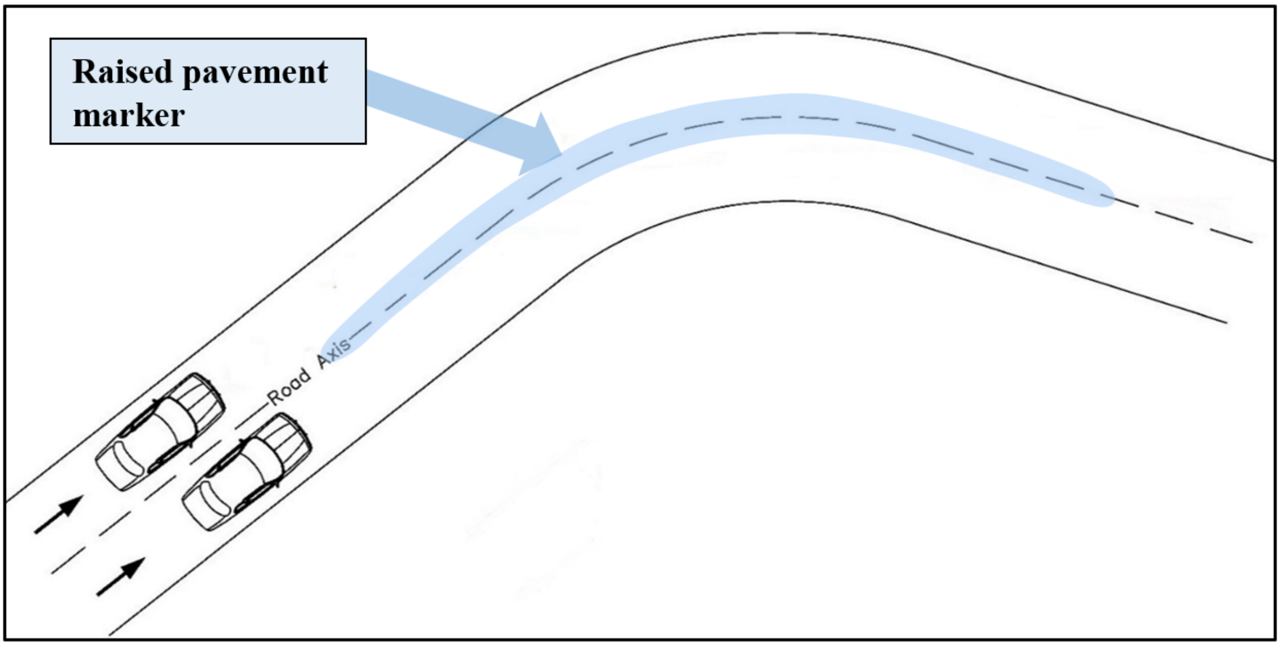

Figure 3.
Setting-up of raised pavement marker.

2.1.4. Transverse Rumble Strips

Transverse rumble strips (TRS), or “in-lane” rumble strips, are a traffic calming measure and warning devices used to alert drivers of upcoming changes in road conditions, such as intersections, pedestrian crossings, or sharp turns and thus to the possible need to take some precautionary action. In other meaningful way, TRS inform drivers that their vehicles are approaching a decision point of critical importance to safety, by mean of vibrations generated when the vehicle's tires pass over them. TRS effectively capture drivers' attention, making them more aware of upcoming changes in road conditions and encouraging them to reduce their speeding by creating an uncomfortable sensation for drivers who are traveling at high speeds. They provide safer driving behaviors and thus they reduce the number of accidents at intersections and other high-risk areas by alerting drivers to potential hazards [17-19]. Yet, the magnitude of the crash effect, as the AMF, of TRS is not certain at this time [10]. However, and rarely, TRS may not be as effective for drivers who are already distracted, as they may not notice the audible warnings or vibrations. Also, TRS may not be as effective in the case of drivers willing to change to other lanes in order to avoid passing over the TRS. Therefore, the TRS treatment is investigated in this research. Figure 4 shows the setting-up of the TRS.

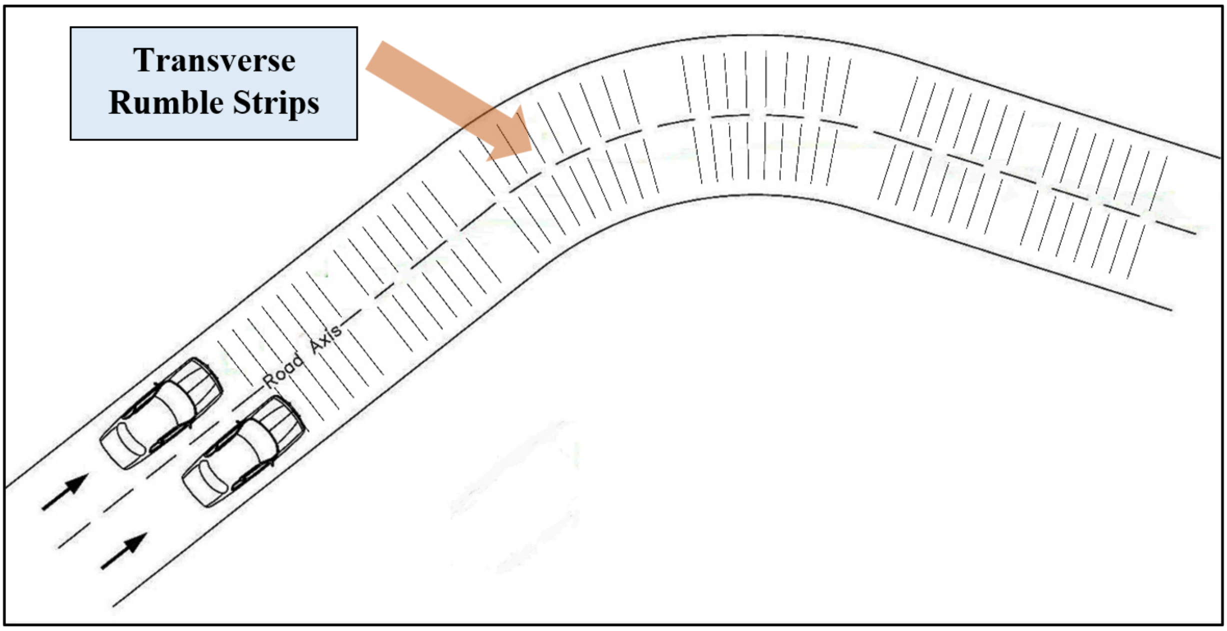

Figure 4.
Proposed setting-up of the transverse Rumble Strips.

2.1.5. Scratched Asphalt Surface

The technique of milling or grinding the asphalt pavement surfaces of roads is often used to improve road safety by increasing friction between the road and vehicle tires. The rougher texture of scratched or grooved asphalt surfaces has several benefits associated with road safety. For instance, Scratched Asphalt Surface (SAS) can increase the friction between the road and vehicle tires, reducing the risk of skidding and improving overall road safety.

Moreover, the grooves created by scratching the asphalt surface can help drain and channel water away from the road by reducing the risk of hydroplaning, decreasing the thickness of water film on a pavement surface, allowing for additional tire-pavement surface interaction during adverse weather conditions and thus improving traction during wet conditions [20]. Moreover, the rougher texture of a SAS can make road markings more visible as the markings stand out against the textured background. The SAS treatment is then investigated in this research. Figure 5 shows the setup of the SAS.

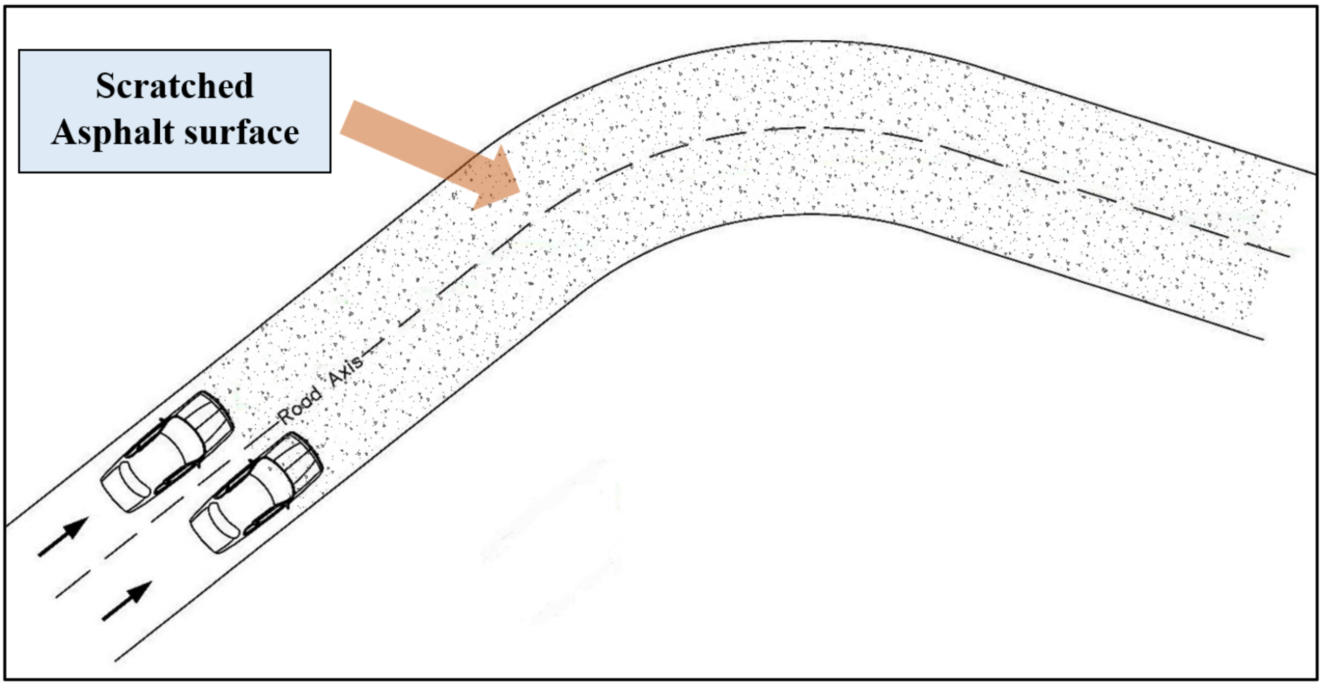

Figure 5.
Proposed setting-up of the scratched asphalt surface.

2.2. Data Collection

A questionnaire survey is conducted through stratified random sampling with direct contact (mainly in parking lots or parking spaces along roadways in Beirut city) with respondents (individuals over the age of 18 and use their private cars for daily trips) in Beirut city, Lebanon, after explaining to them the aim of this study and a brief description of the objectives of this survey. These stratified random contacts, in which the population is divided into subgroups, were adopted to consider and represent the age distribution and the male-female distribution of the whole population of Lebanon, in order to ensure that each subgroup is adequately represented in the final sample. In addition, it is worth noting that the selection of parking lots or parking spaces along roadways in Beirut city follows the simple random sampling technique. The questionnaire is composed of four main question sections about: (a) the social backgrounds of participants: questions on gender, age; (b) the type and size of the generally used cars; (c) identifying the main causes of road crashes at curved road sections as well as the Likert scales that reflect the intensity of the main causes of accidents in curved road section (from 1: least important cause to 5: most important cause); (d) Likert scales for assessing the effectiveness of the three proposed PPLSTs (RPM, TRS, SAS) with respect to each of the identified causes of crashes: from 1 (least important PPLST) to 3 (most important PPLST).

The response rate for the survey is 89.2%, with 446 responses collected from 500 invitations to participate in the survey during November and December 2022. A data cleaning procedure was carried out to remove survey responses that had clearly incorrect Likert scale answers (identical scales for all questions) and significant inconsistencies in responses, such as extreme illogical reasoning regarding the causes of the crash. Regarding the validation of the survey data, rigorous measures were employed to ensure the reliability and internal consistency of the data. The pilot sample of the first 40 observations underwent thorough validation through a test-retest reliability procedure conducted over a period of three weeks prior to the actual start date of the questionnaire data collection. This process yielded similar responses, indicating a strong level of internal consistency among the survey items in the pilot study. Notably, the Cronbach's alpha reliability was not applicable (could not be applicable) for this quantitative survey because the questions involved ranking causes of road crashes (from 1 to 5) and treatment measures (from 1 to 3). The number of valid responses is 361 corresponding to a 95% level of confidence [21] and a 5.16% margin of error, as the population size of Lebanon for the year 2022 is 5,369,616 [22]. The male-to-female ratio of the survey participants is 88.9% (47% male and 53% female of all respondents), whereas the Lebanese Central Administration of Statistics [23] indicated that the male-to-female ratio in Lebanon for the years 2018 and 2019 is 93.7%. Similarly, the age profiles of respondents and their distribution by gender classes, are in conformity of data provided by the

Lebanese Central Administration of Statistics [23] and the reference [22]. These distributions are indicated in Figure 6 and Table 2, respectively. This means that a marginal calibration of the data is not required. The distributions by type of vehicle used is indicated in Table 3.

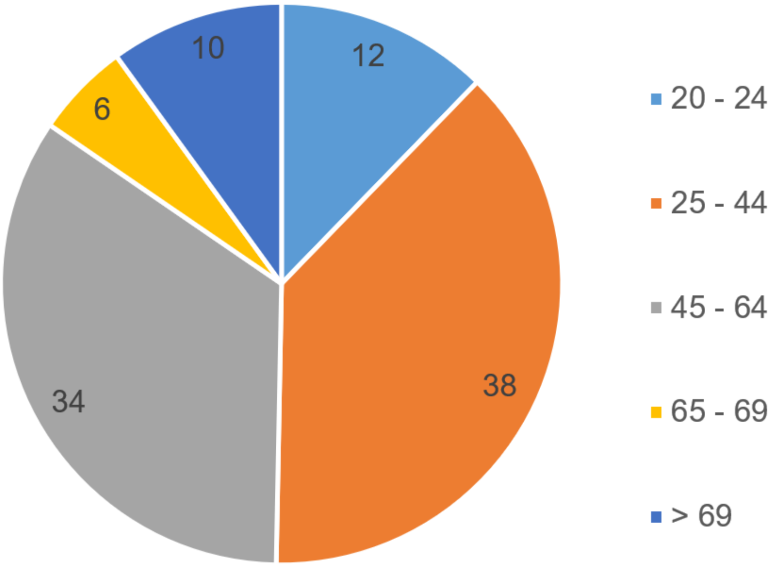

Figure 6.
The age distribution of respondents.

Table 2.
Age Distribution by Gender (%).

Age group	Gender		Total
	Female	Male	
20 - 24	7	5	12
25 - 44	21	17	38
45 - 64	17	17	34
65 - 69	3	3	6
> 69	5	5	10

Table 3.
Distribution by type of vehicle used (%).

Type of vehicle	%
Small	14
Medium	54
Sport Utility Vehicle (SUV)	32

2.3. Application of Multicriteria-Decision Analysis: Analytical Hierarchy Process

Since the study is based on several assessment criteria, the Analytical Hierarchy Process (AHP) is selected to be used to compare, via pairwise comparison matrices, the perceived effects of the different PPLSTs on road crashes in curved road sections. The AHP constitutes a decision-making paradigm that elaborates, through hierarchical structures, the decision problems into a goal, criteria (and sub-criteria in some cases), and alternatives, making it a suitable decision-making tool for comparing the perceived effects of different PPLSTs on road crashes in curved road sections. Through pairwise comparisons and hierarchical structures, AHP enables the quantification of subjective judgments, aiding in the prioritization and ranking of different elements based on their perceived effectiveness. This method not only enhances the transparency and clarity of decision-making but also facilitates the comprehensive evaluation of complex issues in road safety research.

The inclusion of AHP in this study serves to enhance the rigor of the findings by providing a systematic and objective framework for evaluating the effectiveness of PPLSTs in mitigating road crash factors in curved road sections. This comparison involves scaling the comparison criteria as well as the compared alternatives to produce final decision values (percentages) depicting the ranks of the compared alternatives. As the final AHP ranks of the PPLSTs reflect the percentage distribution of their perceived effectiveness, this process allows to determine the perceived most effective PPLST measure, representing the goal of the AHP process. In that context, the PPLST layer represents the alternative level of the structure. The criteria level consists of five factors: (a) high speed driving behavior, (b) the reduced attention of drivers, (c) both high speed coupled with reduced attention, (d) low visibility, and (e) slipping/low stability of vehicles. Figure 7 shows the hierarchical structure of the applied AHP. For more information about the AHP calculation process, readers could refer to Alonso and Lamata [24].

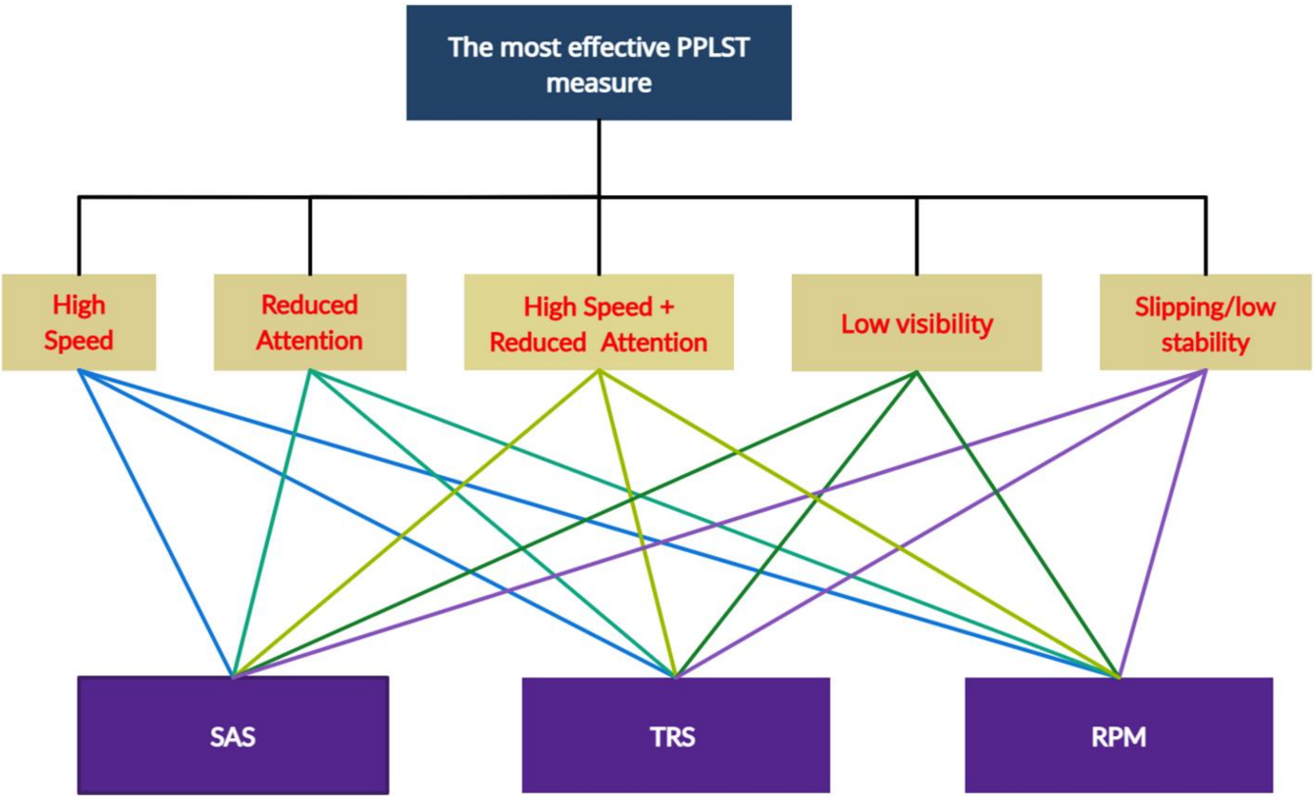

Figure 7.
The adopted AHP structure.

It is worth also noting that in the course of pairwise comparisons integral to AHP, a consistency check is imposed to gauge the reliability of the expert judgments. The Consistency Ratio (CR) emerges as a quantitative metric, computed through the ratio of the Consistency Index (CI) to a Random Index (RI). A CR falling at or below 0.1 is conventionally regarded as acceptable, indicative of judicious internal consistency. Conversely, CR values exceeding 0.1 exact a reassessment by the experts, necessitating refinement of the pairwise comparisons. Furnishing a systematic means to ascertain the stability and dependability of expert judgments, this consistency evaluative mechanism fortifies the integrity of AHP outcomes. It is worth noting that the uncertainty and imprecision introduced by the use of fuzzy MCDA methods are not included in the study, for several reasons. Firstly, the data utilized in the study is clear-cut and precise, without significant uncertainty or imprecision. Consequently, the use of fuzzy sets or fuzzy logic, designed specifically to model vagueness or ambiguity, is reasoned not crucial for the present study Vrtagić et al. [25]; Mitrović et al. [26], and Qin and Zhang [27]. Secondly, the primary objective is to develop a deterministic model for the ranking or evaluation of road sections, based on well-defined criteria, for which a traditional MCDA approach was sufficient [25-27]. In that context, the focus is not to account for uncertainty, but to create a resilient decision-making framework. Additionally, the aim is to present a straightforward and easily interpretable model that does not necessitate the use of fuzzy sets, which could introduce and estimate the uncertainty and imprecision in the analysis.

Finally, the study focuses on developing a practical decision-making framework for road safety evaluation, with the use of fuzzy MCDA falling outside the current study's scope. Therefore, the traditional MCDA approach of the AHP is considered sufficient given the nature and quality of the data available.

3. Results

3.1. Causes of Crashes

The questionnaire results show the main causes of road crashes at curved road sections in descending intensity order as follows: (1) high speed driving behavior coupled with reduced attention, (2) high speed driving behavior, (3) reduced attention, (4) Slipping/ low stability, and (5) Short Sight Distance (Low visibility). The first three causes could logically justify the “cutting-curve driving pattern” that could be induced by an intermediate phase of partially losing control on the vehicle to keep it in its original lane. Slippage represents the fourth main cause of crashes in terms of intensity. This rank could be depicted by the low probability of occurrence limited to rainy weather. The last main cause of this type of crashes is the low visibility restricted by the geometric aspect of curves usually coupled with downward or upward slope of the road. This low intensity could be justified by the case of using very low-height small cars in low lighting conditions. The average scale values for the intensity of these causes are presented in Table 4.

Table 4.
Average perceived importance scales of the cause (values from 1 to 5).

High speed	Reduced attention	High Speed + Reduced attention	Slipping/ low stability	Short Sight Distance (Low visibility)
3.5	2.68	4.92	2.39	1.51

3.2. PPLST Effectiveness with Respect to the Crash Causes

The effectiveness of RPM, in reducing crash rates, is perceived as minimal with respect to other PPLSTs in all cases except that for "short range of sight distance (low visibility)" where the RPMs represent the second effective treatment (scale: 2.16) after the TRS (scale: 2.76). This could be referred to as that in scenarios with reduced visibility, drivers may consider using the RPM as their primary navigation guidance tool. For the remaining cases, three situations are perceived: (a) the TRS are perceived to be slightly higher than that for SAS in the case of "high-speed" and "high-speed coupled with reduced attention" driving behaviors; and (b) the TRS and SAS have the same effectiveness in reducing the crashes rates in the case of "reduced attention" driving behavior; and (c) the SAS have higher effectiveness (scale: 2.81) than that of TRS (scale: 2.19) in the case of "Slipping/ low stability due to centrifugal force on curves". These results (Table 5) could be explained by the perceived (i) high importance of TRS in reducing the driving speed relatively to other treatments, (ii) equal importance of TRS and SAS in providing warning information for drivers in case of any change in road geometries/attributes, and (iii) the high importance of SAS in providing additional stability to vehicles against slippage, especially in the case of rainy weather.

Table 5.
PPLST's scale of effectiveness with respect to crash causes.

Cause of accident	RPM	TRS	SAS
high-speed driving behavior	1.17	2.51	2.32
reduced attention	1.37	2.31	2.32
High speed coupled with reduced attention	1.17	2.58	2.25
Slipping/ low stability due to centrifugal force on curves	1	2.19	2.81
short range of sight distance (low visibility)	2.16	2.76	1.08

3.3. Preferred PPLST as the Most Effective Treatment

Based on the aforementioned scaling results the ranking scales of the preferred treatments are calculated by multiplying the scales of the main causes (Table 4) by those of treatments with respect to each cause (Table 5). The results show that the TRS are the most preferred treatment for 64% of respondents, followed by SAS as the most preferred treatment for 34% of respondents. The RPM are perceived as the most effective treatment by only 2% of respondents.

3.4. Assessment of PPLSTs effects: Application of the Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is conducted to compare, through a hierarchical structure (with comparison criteria) the effectiveness of the PPLSTs, to be presented as the preliminary value of the AMF. The sections are divided into two parts: (i) definition of pairwise comparison matrices to calculate the intermediate AHP ranks for causes and PPLSTs and (ii) calculation of final AHP ranks of PPLSTs and a preliminary estimation of the AMFs for the PPLSTs.

3.4.1. Intermediate AHP Ranks

The comparison of Likert scale responses ranging from 1 to 9 can provide more granular and nuanced insights compared to the standard 5-point scale. Accordingly, and with respect to the crash causes, the differences in average importance scales (from 1 to 5) are multiplied by 2, then rounded to an integer, in order to make the comparison interval extended over a range from 1 to 9. These values are then used in the pairwise comparison matrix (Table 11 in Appendix 1). The rationale behind multiplying the differences in average importance scales (from 1 to 5) by 2 and rounding to an integer is to effectively "stretch" the 5-point scale to a 9-point scale. This approach allows for a more detailed and sensitive measurement of the underlying construct being assessed. While the numerical stretching process of multiplying the 5-point Likert scales by 2 and rounding to an integer does not change the results in terms of the priority order or sequence of significance of the crash causes, extending the scale range from 1-5 to 1-9 can offer researchers a wider spectrum and sensitive measurement of opinions, attitudes, and perceptions from respondents. The intermediate AHP ranks of the main causes of crashes are then presented in Table 6.

Table 6.
AHP ranks of the main causes of crash.

Cause of crash	Rank (%)
High speed	21.10
Reduced attention	11.40
High Speed + Reduced attention	50.80
Slipping/ low stability	10.90
Short Sight Distance (Low visibility)	5.90
Consistency Ratio	0.006

With respect to the PPLSTs, the differences in importance scales (from 1 to 3) are multiplied by 2, then rounded to an integer. It is worth noting that the differences are not multiplied by 3 to prevent extending the comparison interval over a range from 1 to 9 in order to keep a more conservative analysis by considering the minimum comparative difference between the effects of treatments. These values are then used in the pairwise comparison matrix (Tables 12 to 16 in Appendix 1). The intermediate AHP ranks of the main causes of crashes are then presented in Table 7.

Table 7.
AHP ranks of the PPLSTs according to different case of crash causes.

	AHP Rank (%)				
With respect to PPLST type	**High speed**	**Reduced attention**	**High Speed + Reduced attention**	**Slipping/ low stability**	**Short Sight Distance**
RPM	17	20	17	15	38.7
TRS	44.3	40	44.3	37.6	44.3
SAS	38.7	40	38.7	47.4	17
Consistency Ratio	0.019	0	0.019	0.056	0.019

3.4.2. Final AHP Comparison and Preliminary Estimation of the Accident Modification Factor

Based on the aforementioned results, the effectiveness values of the TRS and SAS are both more than double of that of RPM. The final AHP ranks of the PPLSTs' effectiveness are presented in Table 8. It is worth noting that, for AADT < 20,000, the effect of RPM, which increases the speed of traffic and as a result the crash rates also, does not apply in the case of a multilane one-direction curved road section. For the preliminary estimation of the AMF for the TRS and SAS, the AMFs for the RPM in the case of AADT > 20,000 are taken into consideration. As a result, and according to the Highway Safety Manual of the year 2010 (AASHTO, 2010), the AMFs for TRS and SAS, when preventing lane changes in one direction multilane curved road, would be less than 0.94 (for an annual average daily traffic between 20,001 to 60,000) and 0.67 (for an annual average daily traffic over 60,000).

Table 8.
Final AHP ranks of the PPLSTs perceived effectiveness.

PPLST type	Rank (%)
RPM	18.4
TRS	43.1
SAS	38.5

4. Cross-analysis and Discussion

4.1. Causes of Crashes: Insights According to Gender, Age and Type of Vehicles Used

With respect to the stated mean intensities of crash causes (ranging from 1: least important cause to 5: most important cause), no significant differences are noticed among gender and age classes as indicated in Tables 9 and 10. This means that the causes of crashes are perceived the same for both men and women drivers and for all adult age groups.

Table 9.
Causes of crashes: Insights according to gender classes.

Gender	High speed	Reduced attention	High Speed + Reduced attention	Slipping/ low stability	Short Sight Distance (Low visibility)
Female	3.47	2.63	4.92	2.39	1.59
Male	3.51	2.73	4.92	2.40	1.42
Average	3.49	2.68	4.92	2.395	1.505

Table 10.
Causes of crashes: Insights according to age classes.

Age range	High speed	Reduced attention	High Speed + Reduced attention	Slipping/ low stability	Short Sight Distance (Low visibility)
20 - 24	3.40	2.74	4.90	2.48	1.48
25-44	3.24	2.71	4.82	2.65	1.58
45-64	3.72	2.67	5.00	2.21	1.39
65-69	3.45	2.91	5.00	2.00	1.64
> 69	3.78	2.41	5.00	2.19	1.59
Average	3.52	2.69	4.94	2.31	1.54

With respect to the types of vehicles used, several differences among the stated causes of crashes are noticed. Users of small cars perceive reduced attention while driving as a less important cause of crashes compared to the users of other vehicle sizes. In contrast, small car users consider low visibility to be a more significant factor compared to other vehicle users, as indicated in Figure 8.

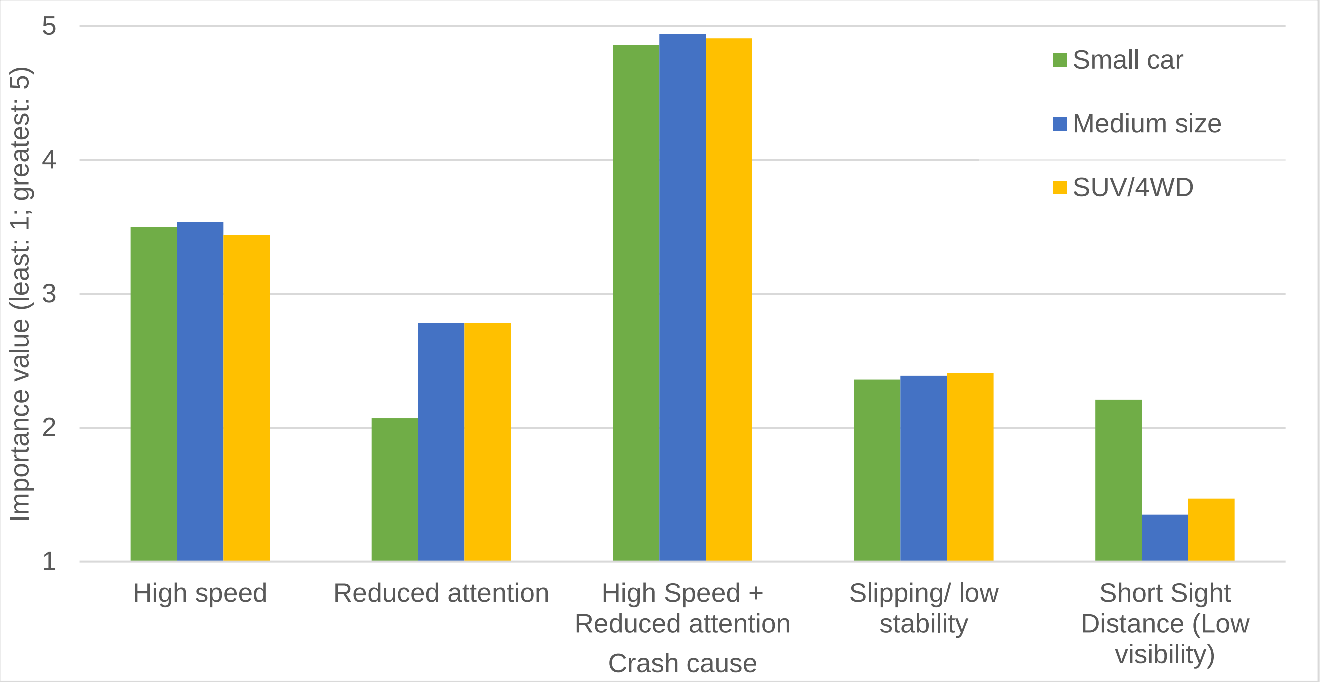

Figure 8.
Causes of crashes: Insights according to the types of vehicles used.

4.2. Effectiveness of Treatments with Respect to the Crash Causes: Insights According to Gender, Age and Type of Vehicles Used

The results indicating varying perceptions of road safety measure effectiveness between gender classes provide valuable insights into the factors that may contribute to these perceptions. With respect to gender classes, 65.4% of females perceive the TRS as the most effective PPLST, while 61.2% of males share the same perception (Figure 9). For the SAS, 30.9% of female drivers and 38.8% of male drivers consider it the most effective PPLST. Regarding the remaining PPLST, the RPM, only 3.7% of female drivers perceive it as the most effective treatment. The differences in perceived effectiveness between gender classes may be attributed to variations in driving habits and preferences. For instance, female drivers may be more cautious and attentive to road safety measures, leading to higher perceived effectiveness of TRS. Also, female drivers may have a higher risk perception, leading them to appreciate the immediate feedback provided by TRS more than male drivers. This could contribute to the higher perceived effectiveness of this measure among female drivers. In contrast, male drivers may have different driving habits that make them more receptive to the grooved asphalt surface. Regarding the effectiveness of all proposed treatments for each crash cause, no significant differences are observed between gender classes, as shown in Figure 12 in Appendix 2.

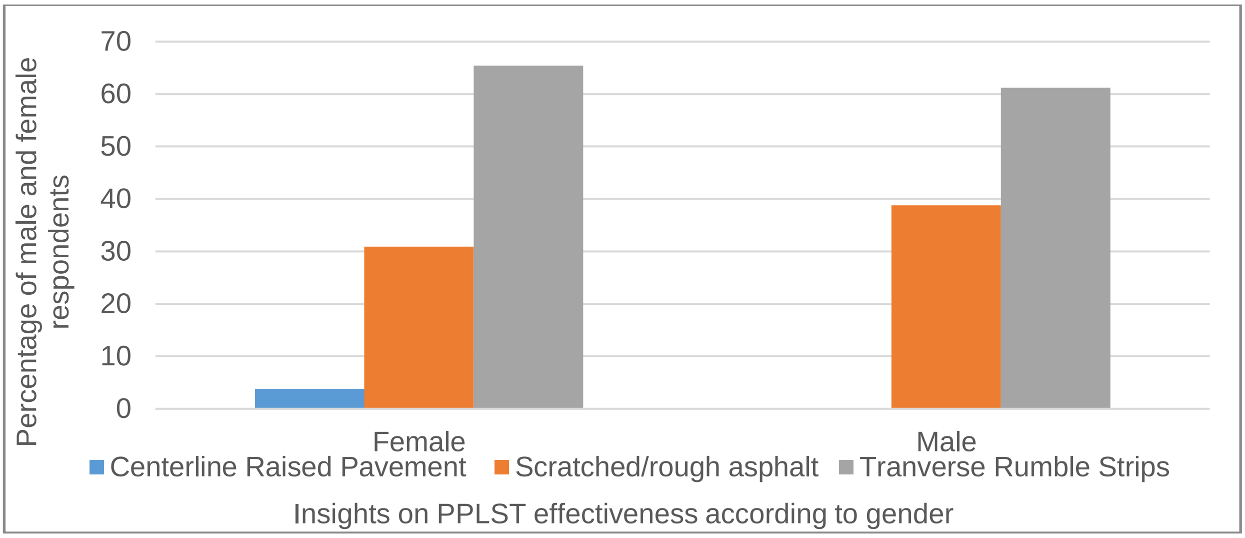

Figure 9.
Effective treatment: Insights according to gender.

The varying effectiveness of road safety treatments in addressing the primary causes of road accidents across different age groups must also be examined. The data also reveals that perceptions of effectiveness vary across age classes, suggesting that factors such as driving experience, risk perception, and familiarity with road safety measures may influence these perceptions. For the 25-44 and 45-64 age groups, TRS are perceived as the most effective treatment, with 76.6% and 70.5% effectiveness, respectively (Figure 10). This may be attributed to the immediate feedback provided by TRS, which could be particularly appealing to drivers with more driving experience. In contrast, the 20-24, 65-69, and >69 age groups consider SAS as the most effective treatment, with 54.5%, 81.8%, and 54% effectiveness, respectively. The higher perceived effectiveness of SAS among these age groups could be referred to their driving habits and attentiveness. RPM has the lowest perceived effectiveness across all age groups. Its maximum value of 8% was reached in the >69 age group. This may indicate that older drivers are more sensitive to this road safety measure, possibly due to their increased risk perception, driving experience and visual focus.

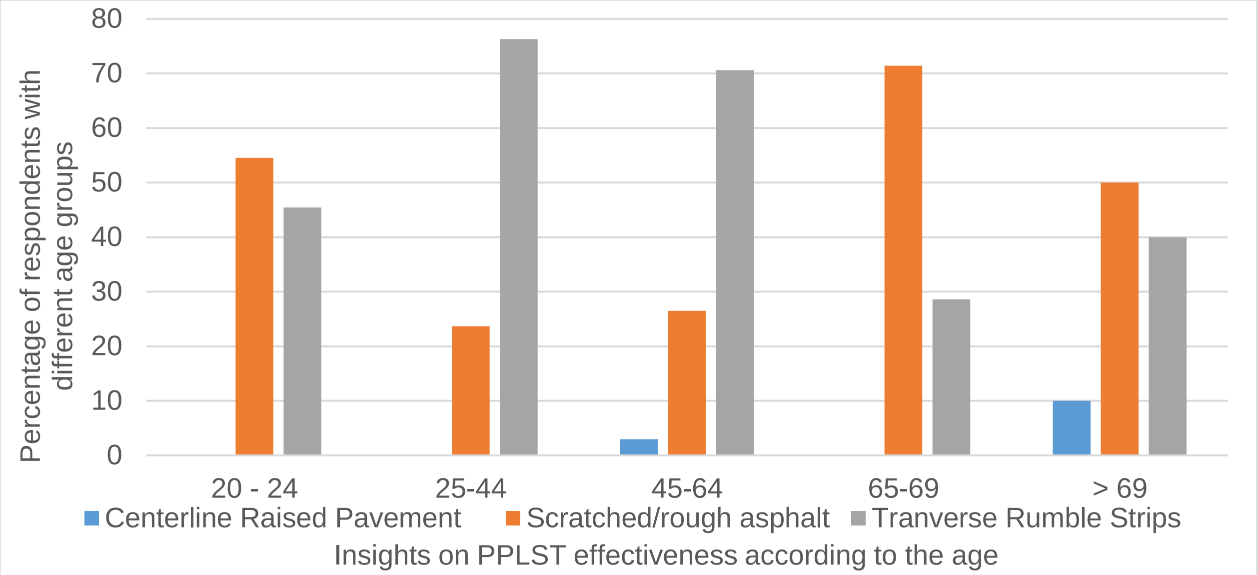

Figure 10.
Preferred treatment - Insights according to age.

Moreover, the survey data reveal that, for all age groups, the RPM was consistently perceived as the least effective treatment across the majority of accident causes except when addressing the case of short sight distance and low visibility where it represents the second most effective road safety treatment after the TRS as indicated in Figure 13 in Appendix 3. Also, for all age groups, the TRS and the SAS showed different moderate to highest effectiveness. For the age group 20-24, TRS exhibits the greatest efficacy in reducing the crash rates caused mainly by high-speed driving behavior and low visibility over curved road sections. SAS proves to be the most effective treatment for reduced attention and the combination of high-speed and reduced attention driving behavior as well as the cases of slipping/low stability, as indicated in Figure 13 in Appendix 3. This could be explained by that the 20-24 age group may be more prone to high-speed driving behavior, the TRS can be particularly effective in capturing their attention and prompting them to slow down. Additionally, the noise and vibration produced by the TRS when vehicles pass over them can help increase awareness in low visibility situations on curved road sections where visibility might be further reduced, especially during nighttime or foggy conditions. Also, for drivers with reduced attention or those exhibiting a combination of high-speed and reduced attention driving behavior, the increased friction can help maintain vehicle stability and control, reducing the risk of crashes. The rougher surface may also provide a tactile cue to drivers, reminding them to pay attention to their driving and potentially reducing instances of inattentive driving. For individuals aged 25-44, TRS shows the highest effectiveness for all cases of crash causes except for the case of slipping/low stability, where the optimal perceived treatment is the SAS. This could be explained as individuals aged 25-44 are generally more experienced drivers than younger age groups, but they may also be more prone to distractions or fatigue due to work, family, or other responsibilities; and TRS can be particularly effective for this age group because they provide a physical and audible warning that can quickly refocus a driver's attention on the road.

However, in cases of slipping or low stability, SAS emerge as the most effective treatment because it can provide increased friction between the road and a vehicle's tires, which can help to improve traction and stability, particularly in wet or slippery conditions, contrarily to TRS which may not directly address the issue of slipping or low stability. Moreover, the vibrations caused by TRS could even exacerbate slipping or stability issues, particularly if the driver is struggling to maintain control of the vehicle. For individuals aged 45-64, TRS show the highest effectiveness for all cases of crash causes except for the cases of reduced attention driving behavior and slipping/low stability where the optimal perceived treatment is the SAS. Individuals aged 45-64 are generally more experienced drivers and may have better-developed driving skills than younger age groups. However, they may also be more prone to distractions, fatigue, or age-related declines in cognitive function. TRS can be particularly effective for this age group because they provide a physical and audible warning that can quickly encourage them to slow down. However, in cases of reduced attention driving behavior and slipping/low stability, TRS may not be as effective as a SAS since the latter can (i) be more effective in providing a tactile cue to drivers, reminding them to pay attention to their driving, and (ii) can help to improve traction and stability, particularly in situations where slipping or low stability is a primary crash cause. For individuals aged 65-69, SAS shows the highest effectiveness for all cases of crash causes except for the case of short sight distance/low visibility where the optimal perceived treatment is the TRS. Individuals in this age group are generally more experienced drivers, but they may face age-related declines in cognitive function, reaction time, and diminished physical abilities. A SAS can be particularly effective for individuals in this age group, where those drivers may have slower reaction times or diminished physical abilities, because it addresses various crash causes, such as reduced attention, and provides increased friction between the road and a vehicle's tires, which can help to improve traction and stability. However, in cases of short sight distance/low visibility, TRS may be more effective since their audible and tactile warning, about the road geometry, can be particularly helpful in refocusing a driver's attention on the road geometry and alerting to potential hazards. This is because TRS create more intense vibrations and noise, relatively to SAS, when vehicle tires pass over them. Lastly, drivers aged 69 and above may also face age-related declines in cognitive function, reaction time, and physical abilities. These factors can contribute to an increased risk of crashes due to reduced attention, high-speed driving behavior, and slippage. For this age group, TRS are perceived as the most effective PPLST for, reduced attention, and for the case of high-speed driving behavior coupled with reduced attention as well as for the case of low visibility. Besides, SAS emerges as the most effective treatment for high-speed driving behavior as well as for slippage. Additional investigations are required to identify the reasons behind these differences. Besides, since small, medium-sized vehicles, and SUVs have different handling characteristics, center of gravity, and tire contact patches (these factors can influence how vehicles interact with various road safety treatments) and since the perceptions of PPLST effectiveness may also be influenced by the drivers' experiences and expectations, drivers of different vehicle types may have varying levels of familiarity with specific PPLST, which could affect their perceptions of effectiveness. Additionally, drivers may have different expectations regarding the performance of these measures based on their vehicle type. Hence, the findings indicate that the perception of PPLSTs effectiveness, as a good road safety measure, varies depending on the vehicle type. Specifically, RPM is perceived as the most effective treatment by 5.7% of SUV users, while small and medium-sized car users report no perceived effectiveness. This difference in perceived effectiveness could be explained by the fact that SUVs typically have higher ground clearance and more robust suspension systems, making Centerline RPM more noticeable and effective for drivers of these vehicles. In contrast, drivers of small and medium-sized cars may not experience the same level of impact from this measure due to their vehicles' lower ground clearance and different suspension systems, which could lead to lower perceived effectiveness. In contrast, SAS is considered effective by 42.8% of Small car users, 34% of Medium-sized car users, and 29% of SUV users. This could be explained by the small cars, with their lower ground clearance and lighter weight, may be more sensitive to the SAS, leading to higher perceived effectiveness. In contrast, Medium-sized cars and SUVs, which are generally heavier and have higher ground clearance, may not experience the same level of impact from the SAS, resulting in lower perceived effectiveness. With respect to TRSs, they provide immediate feedback to drivers by creating vibrations and audible noise when a vehicle crosses over them. TRS are perceived as the most effective treatment across all vehicle types, with 57.2% of small car users, 66% of medium-sized car users, and 65.3% of SUV users reporting effectiveness as indicated in Figure 11. These differences highlight the varying perceptions of road safety measure effectiveness among different vehicle types and emphasize the importance of considering these differences when evaluating and implementing further road safety interventions.

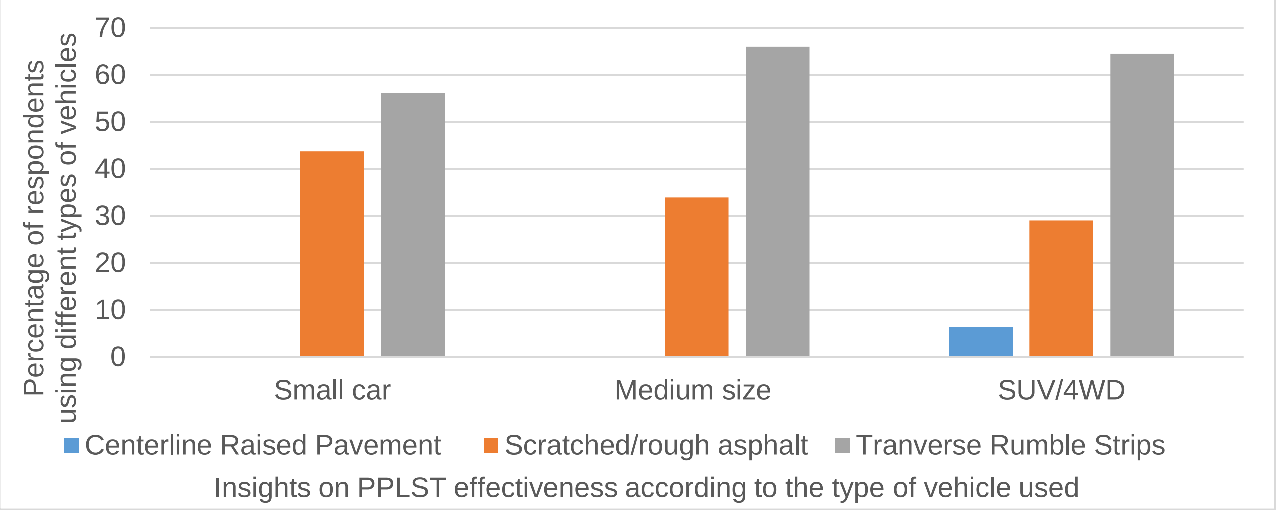

Figure 11.
Preferred treatment - Insights according to type of vehicles used.

The results revealed that, for small, medium-sized vehicles and SUVs, RPM was consistently perceived as the least effective treatment across the majority of accident causes except for the case of short sight distance and low visibility where it represents the second most effective road safety treatment after the TRS as indicated in Figure 14 in appendix 4. RPMs are primarily designed to improve lane delineation and visibility, but they may not directly address other common accident causes, such as speeding, inattention, or failure to yield. This limited scope of effectiveness could contribute to the perception that RPMs are less effective than other treatments, such as TRS or SAS, which can address a broader range of accident causes. Additionally, RPMs can sometimes create a bump or uneven surface when vehicle tires pass over them. For some drivers, this bump may be perceived as uncomfortable or even cause a momentary loss of control, particularly for smaller vehicles with less suspension travel. This potential negative effect could contribute to the perception that RPMs are less effective than other road safety treatments. However, in cases of short-sightedness and low-visibility, RPMs may be perceived as more effective since they can improve lane delineation and visibility in low-light or adverse weather conditions. This finding suggests that RPMs may be more beneficial in specific driving conditions, warranting further investigation. The TRS demonstrated the highest effectiveness against the primary causes of crashes, for medium-sized vehicles and SUVs, except in the case of slippage for both types of vehicles, as well as the case of reduced attention driving behavior for medium-sized vehicles, where the SAS exhibited the highest perceived effectiveness. This indicates that the effectiveness of road safety treatments varies depending on specific accident causes and vehicle types, highlighting the need for tailored interventions. In cases of slippage, TRS may not be as effective as SAS. This is because the vibrations caused by rumble strips could exacerbate slipping or stability issues, particularly for medium and SUVs that have more weight than small cars. Besides, for medium-sized vehicles, which have a lower center of gravity and more agile handling compared to SUVs, the tactile feedback provided by SAS might be more effective in refocusing a driver's attention on the road. For small-sized vehicles, the TRS demonstrated the highest effectiveness against the primary causes of crashes, except in the cases of slippage and high-speed driving behavior, where the SAS exhibited the highest perceived effectiveness. For small-sized vehicles, which generally have lighter weight and smaller tire contact patches, the audible and tactile warning provided by TRS can be particularly effective in alerting drivers to potential hazards and addressing various crash causes, such as inattention or reduced attention driving behavior, and low visibility in curved road sections. In contrast, TRS may not be as effective as SAS. This is because the vibrations caused by rumble strips could exacerbate slipping or stability issues, particularly for small-sized vehicles with less suspension travel and a smaller tire contact patch. Similar to the case of other vehicle types, SAS exhibited the highest perceived effectiveness in the cases of slippage, and this is likely because the rough texture provides more traction and stability, making it harder for tires to skid.

Nonetheless, and differently to other vehicle types, at higher speeds, the rumble strips may not provide enough of a vibration or audible warning to prompt the driver to slow down or correct their course. Instead, the rougher road surface as the SAS is more physically disruptive for small cars at higher speeds. The results of this study provide valuable insights into the perceived effectiveness of various road safety treatments for small, medium-sized vehicles, and SUVs against different types of crash causes. It is worth noting that these results are based on perceptions and may not necessarily reflect the actual effectiveness of these treatments in real-world scenarios. Further research, including simulations, controlled studies and field evaluations, is needed to validate these perceptions and determine the true effectiveness of these road safety treatments in reducing accidents.

5. Conclusion and Future Research

The scientific literature indicates that road traffic crashes have been observed on curved road sections more than on straight ones. This type of road crash could occur in two cases: (i) between two different directions of traffic, and (ii) among the traffic passing in a multilane one-direction road section. The latter case usually corresponds to highways with physical separations between the two directional traffic. Within this particular case, the driving behavior denoted by “curved cutting” could be the main cause of traffic crashes. The main determined causes have been identified by the literature as the drivers’ behaviors and the road geometry. This study analyzes the perceived effectiveness of the implementation of a new road safety measure consisting of the installation of partial physical lane separation treatments (PPLST) within the road pavement layer. Three types of PPLST were introduced: (i) raised pavement markers, (ii) transverse rumble strips, and (iii) scratched asphalt surface. The changes in crash rates on multilane one-direction curved road sections, before and after the implementation of the PPLST, are identified in this research. The comparative analysis gives an overview of the effectiveness of the proposed measure. The perceived induced effects of the proposed safety measure on driving behavior in curved sections, as well as the main causes of crashes in curved multilane one-direction road sections, are examined and evaluated according to an intensity scale through a questionnaire survey. This survey encloses the human reaction stimulated by the induced dynamic road-vehicle vibrations in addition to the visual information the driver will capture. According to the answers, the main causes of crashes are divided into five categories: (i) high-speed driving behavior, (ii) reduced attention as reckless driving behavior, (iii) both high-speed and reduced attention, (iv) slipping/low stability of the vehicle, and (v) short sight distance as low visibility on curves. Results obtained via the questionnaire indicate that: (a) combined high-speed and reduced attention driving behavior followed by high-speed driving are the main causes of crashes in the said road sections; and (b) that the transverse rumble strip is perceived by the majority of respondents (64%) as the most effective solution followed by the SAS (34%). These results are further employed in a multicriteria decision analysis, using the Analytical Hierarchy Process, in order to estimate preliminary values of AMF for the proposed PPLSTs relative to that of the RPM. The comparison was conducted according to the main causes of crashes, considered as the decision criteria.

Results show the percentages of 18.4, 38.5, and 43.1 respectively for RPM, SAS, and TRS. With respect to that result, and according to the Highway Safety Manual of the year 2010 (AASHTO, 2010), the AMFs of TRS and SAS are less than 0.94 (for an annual average daily traffic between 20,001 and 60,000) and 0.67 (for an annual average daily traffic over 60,000). This research could be extended to take into consideration different scenarios related to road attributes such as: (a) the radius of the curve, (b) the number of lanes, (c) speed limits, (d) curvature direction (to the left or to the right), (e) vertical direction of the curve (horizontal, downward, upward), and (f) the location of the vehicle in the inner or outer lane. Additionally, the research could be extended to investigate the perception of drivers of other types of vehicles. This study combines human behavior science, transportation engineering (enhancement of pavement design), and traffic safety science. The results indicate the level of effectiveness of the proposed measure in reducing the number of crashes and the corresponding rates. The outcomes are instrumental in informing targeted road safety interventions and policies to enhance overall road safety and could provide some useful insights for implementing the artificial algorithm of autonomous vehicles. In particular, decision-makers could rely on this data to enact new policies and norms related to the design of roads and driving behaviors/restrictions to enhance overall road safety. Further research, including driving simulations, controlled studies, field evaluations, and the assessment of the impacts of design/dimensions for the raised pavement marker on traffic safety, is needed to validate these perceptions and determine the true effectiveness of these road safety treatments in reducing accidents. Moving forward, it is recommended that future research endeavors consider incorporating the evaluation of uncertainty using Fuzzy methods such as Fuzzy AHP and Fuzzy Topsis. By integrating these advanced analytical tools, future studies can better assess the impact of uncertainties on road safety evaluations, leading to more informed decision-making processes. This approach will not only enhance the depth of analysis but also contribute to the advancement of knowledge in the field of road safety evaluation, ultimately guiding the development of more effective and evidence-based road safety interventions.

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Appendix 1

Table 11.
Pairwise comparison matrix of the effects of accident causes.

	High speed	**Reduced attention**	**High Speed + Reduced attention**	**Slipping/ low stability**	**Short Sight Distance (low visibility)**
High speed	1	2	1/3	2	4
Reduced attention	1/2	1	1/4	1	2
High Speed + Reduced attention	3	4	1	5	7
Slipping/ low stability	1/2	1	1/5	1	2
Short Sight Distance (low visibility)	1/4	1/2	1/7	1/2	1

Table 12.
Pairwise comparison matrix of the effectiveness of treatments with respect to high-speed driving behavior.

	RPM	**TRS**	**SAS**
RPM	1	1/3	1/2
TRS	3	1	1
SAS	2	1	1

Table 13.
Pairwise comparison matrix of the effectiveness of treatments with respect to reduced attention.

	RPM	**TRS**	**SAS**
RPM	1	1/2	1/2
TRS	2	1	1
SAS	2	1	1

Table 14.
Pairwise comparison matrix of the effectiveness of treatments with respect to high-speed and reduced attention driving behavior.

	RPM	**TRS**	**SAS**
RPM	1	1/3	1/2
TRS	3	1	1
SAS	2	1	1

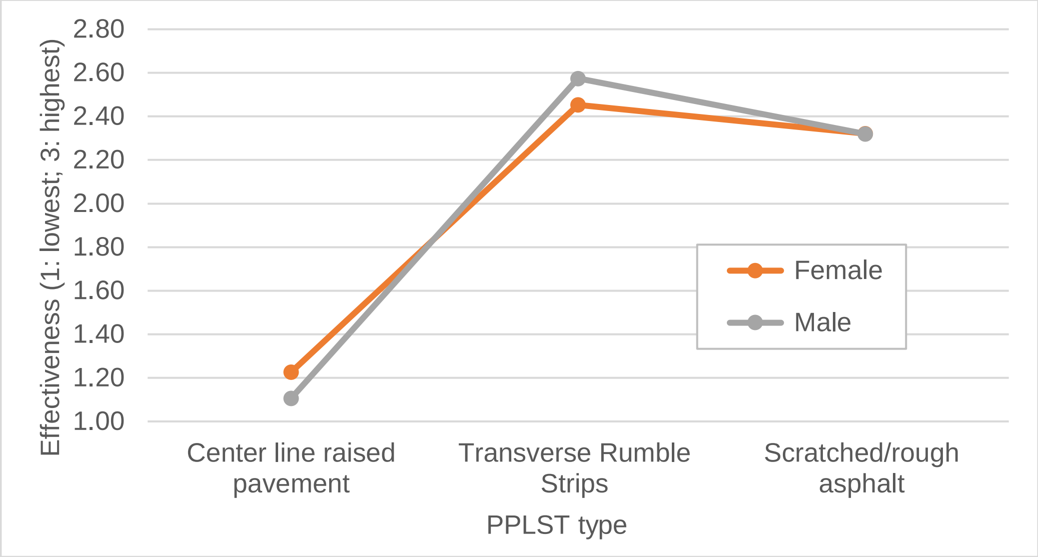
Table 15.
Pairwise comparison matrix of the effectiveness of treatments with respect to Slipping/ low stability of vehicle.

	RPM	**TRS**	**SAS**
RPM	1	1/2	1/4
TRS	2	1	1
SAS	4	1	1

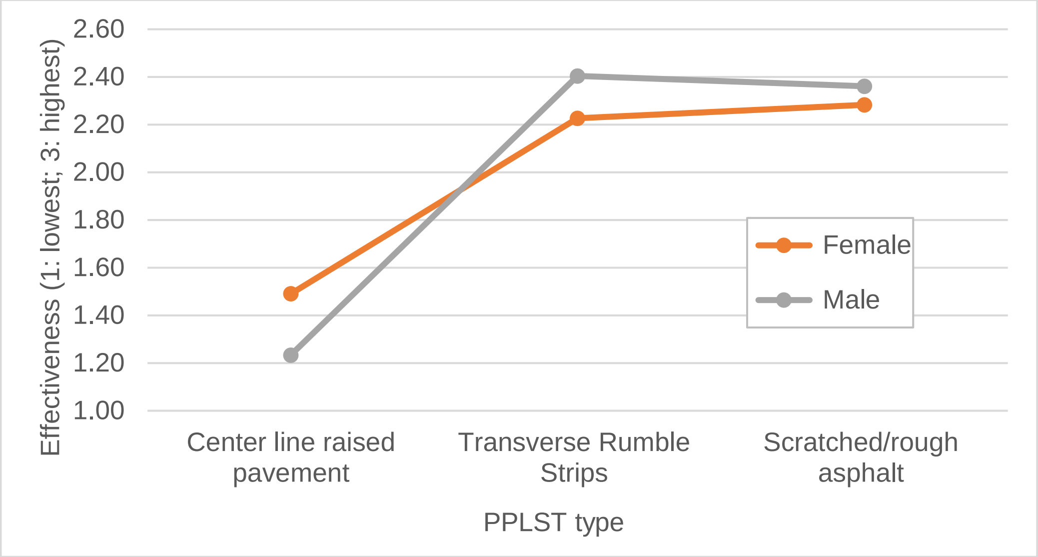
Table 16.
Pairwise comparison matrix of the effectiveness of treatments with respect to Short Sight Distance (Low visibility).

	RPM	**TRS**	**SAS**
RPM	1	1	2
TRS	1	1	3
SAS	1/2	1/3	1

Appendix 2



(a)



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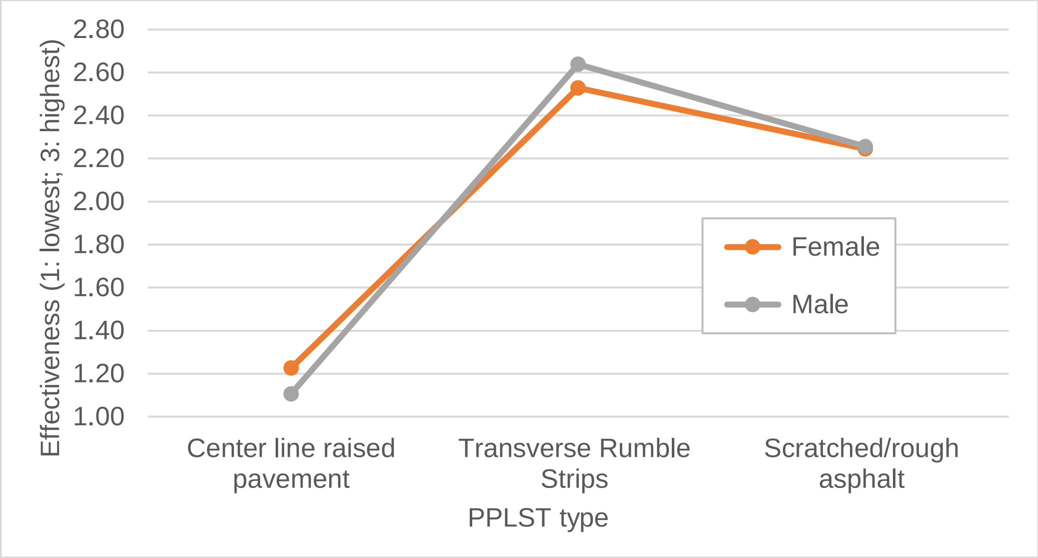

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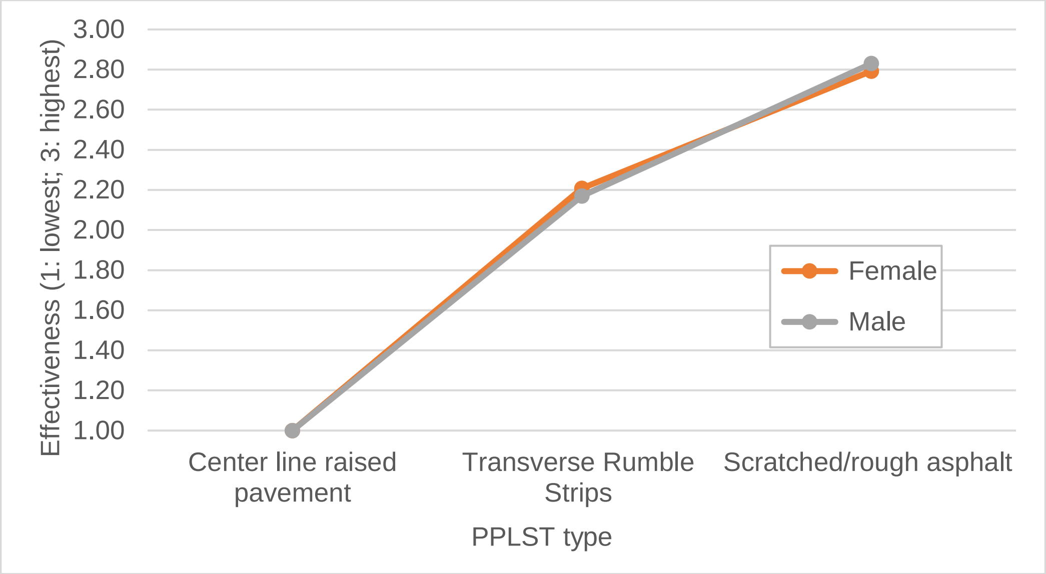

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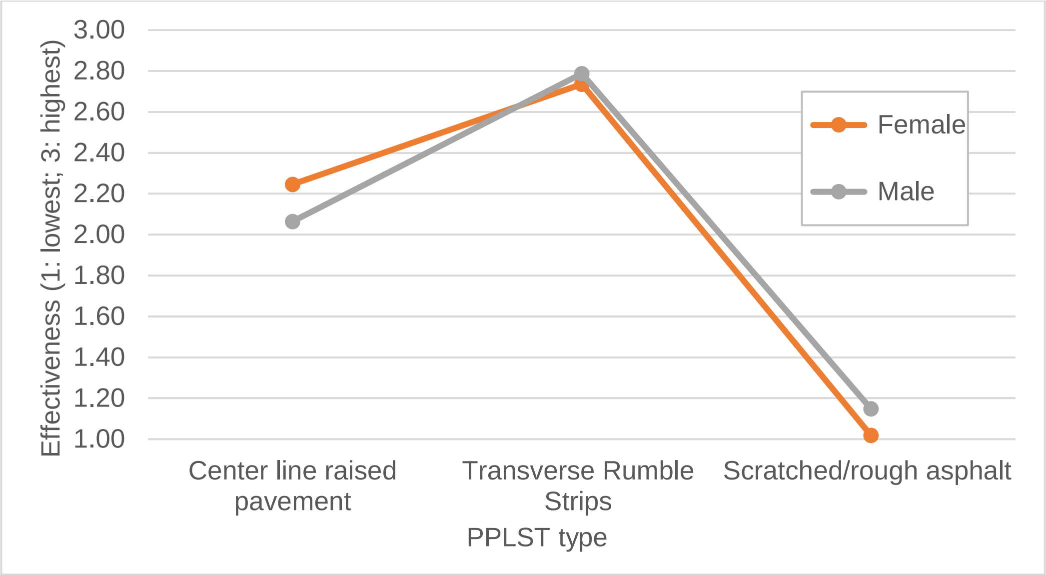
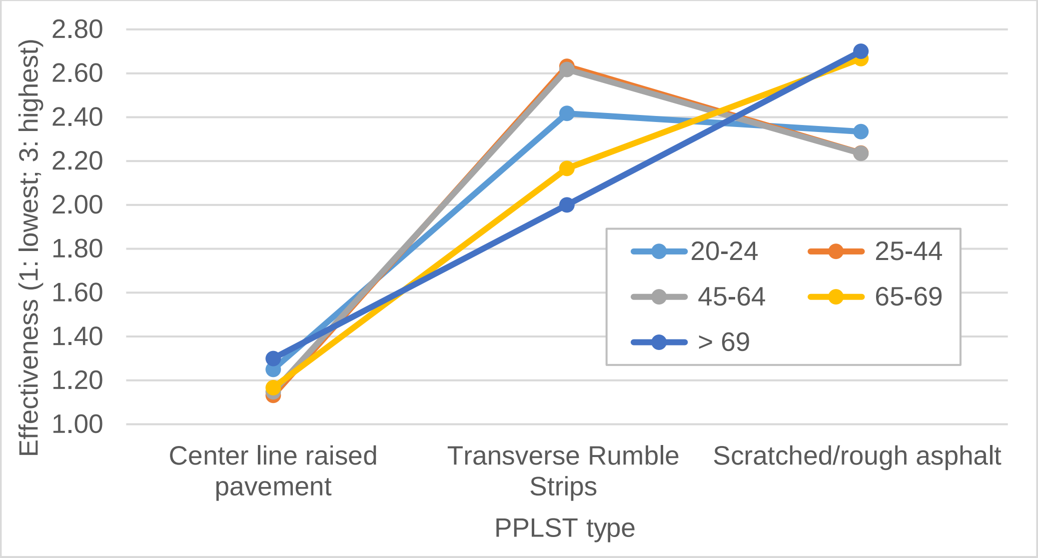
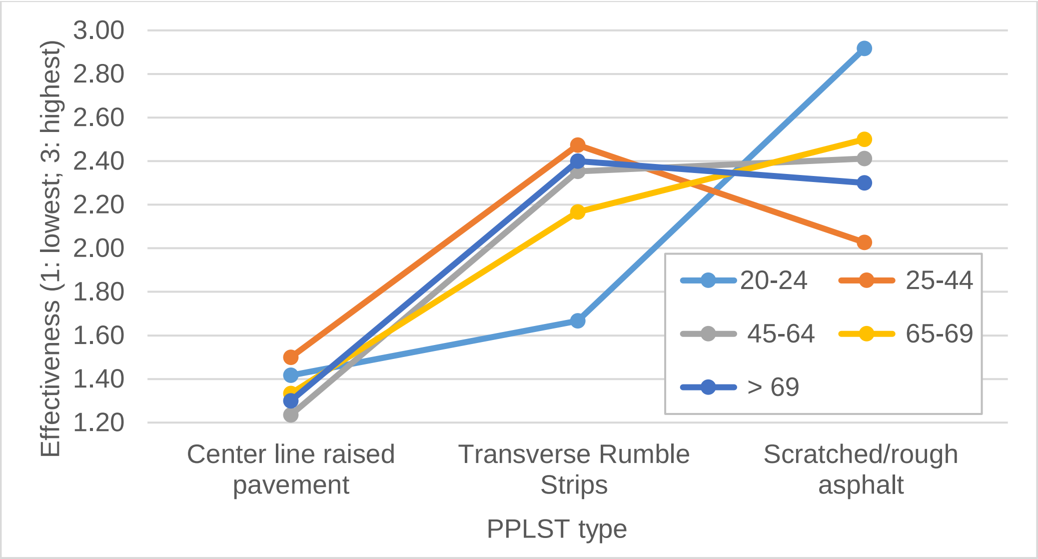


(e)

Figure 12.
Effective PPLST as a treatment for crash causes - Insights according to gender: (a) High speed, (b) Reduced attention, (c) High speed + Reduced attention, (d) Slipping/ low stability, (e) Short Sight Distance (Low visibility).

Appendix 3





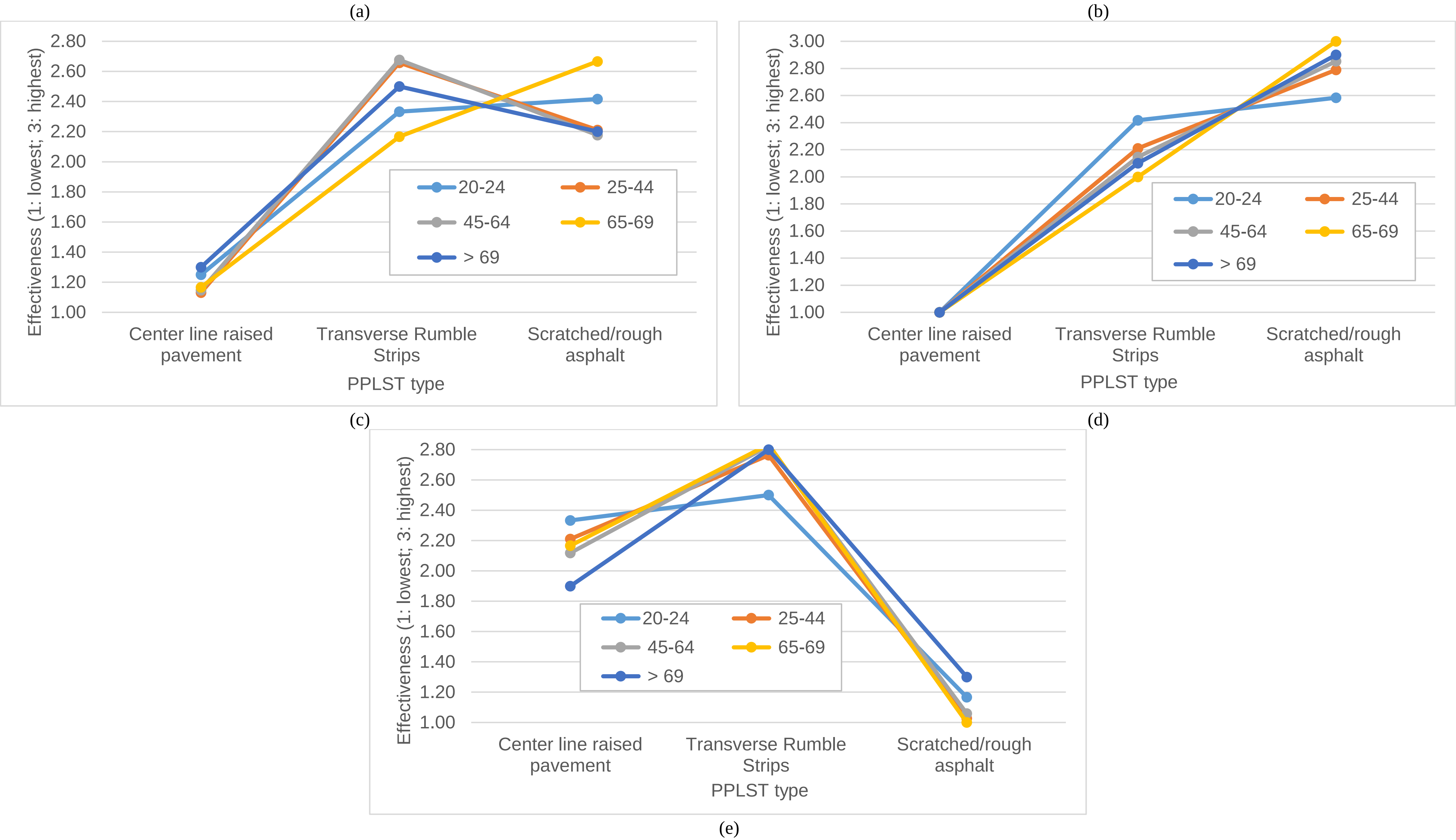
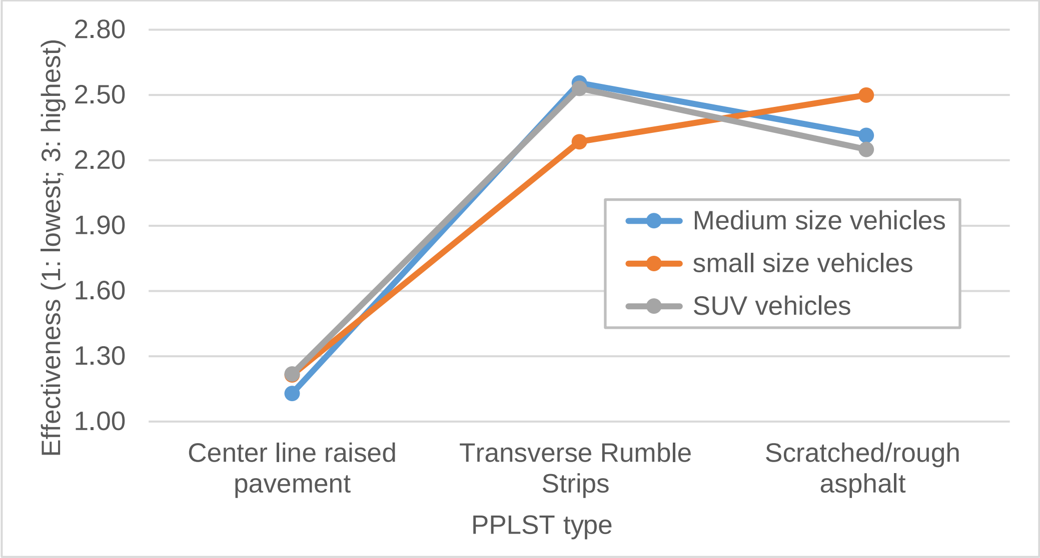


Figure 13.
Effective PPLST as a treatment for crash causes - Insights according to age: (a) High speed, (b) Reduced attention, (c) High speed + Reduced attention, (d) Slipping/ low stability, (e) Short Sight Distance (Low visibility).

Appendix 4



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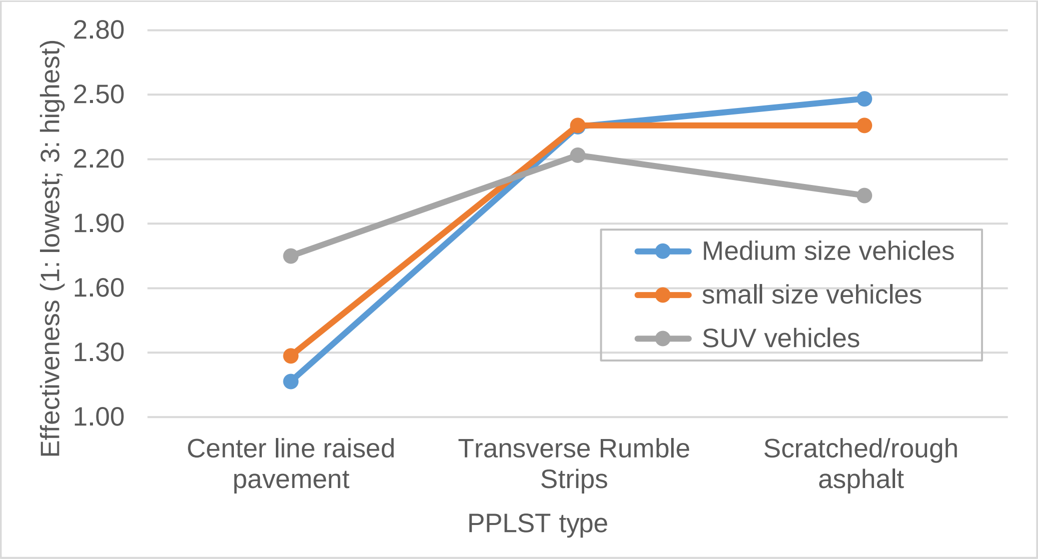

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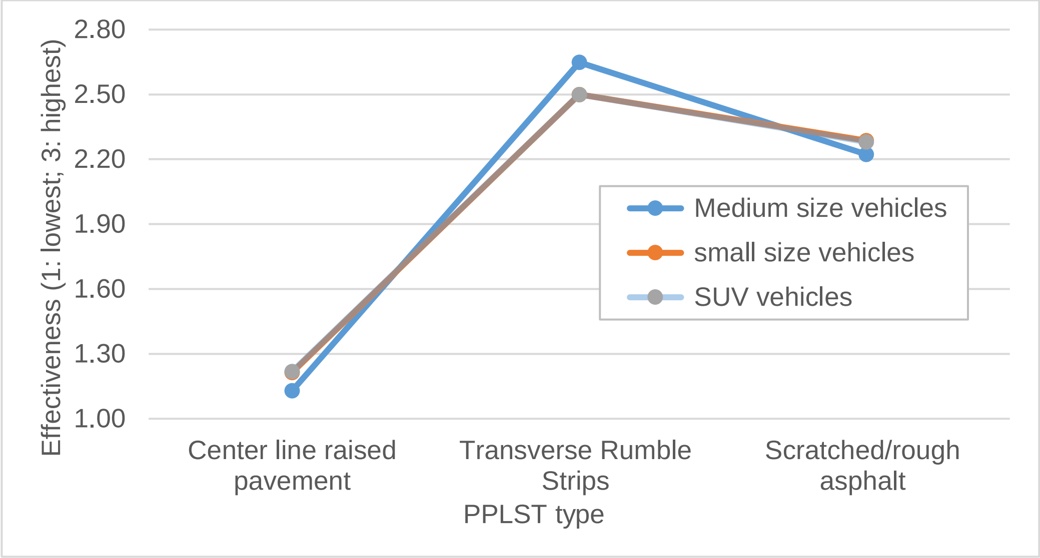

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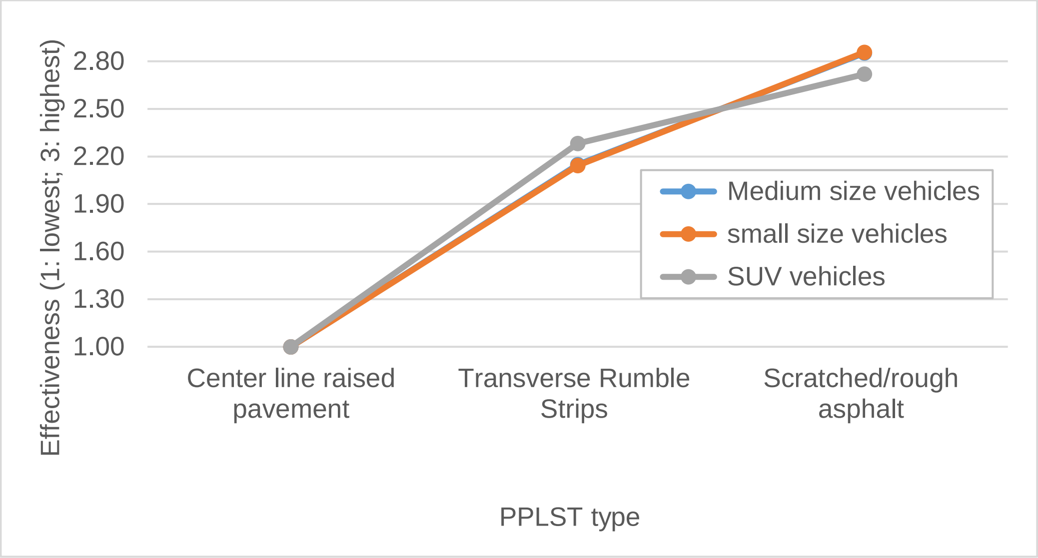
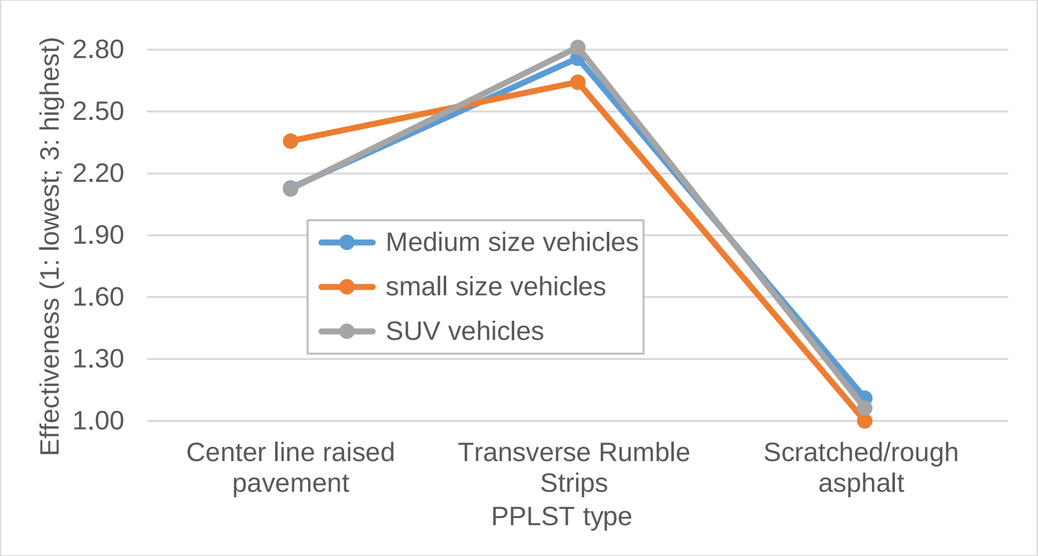


(d)



(e)

Figure 14.
Effective PPLST as a treatment for crash causes - Insights according to types of vehicles used: (a) High speed, (b) Reduced attention, (c) High speed + Reduced attention, (d) Slipping/ low stability, (e) Short Sight Distance (Low visibility).